Search for Dark Matter with the CDMS experiment

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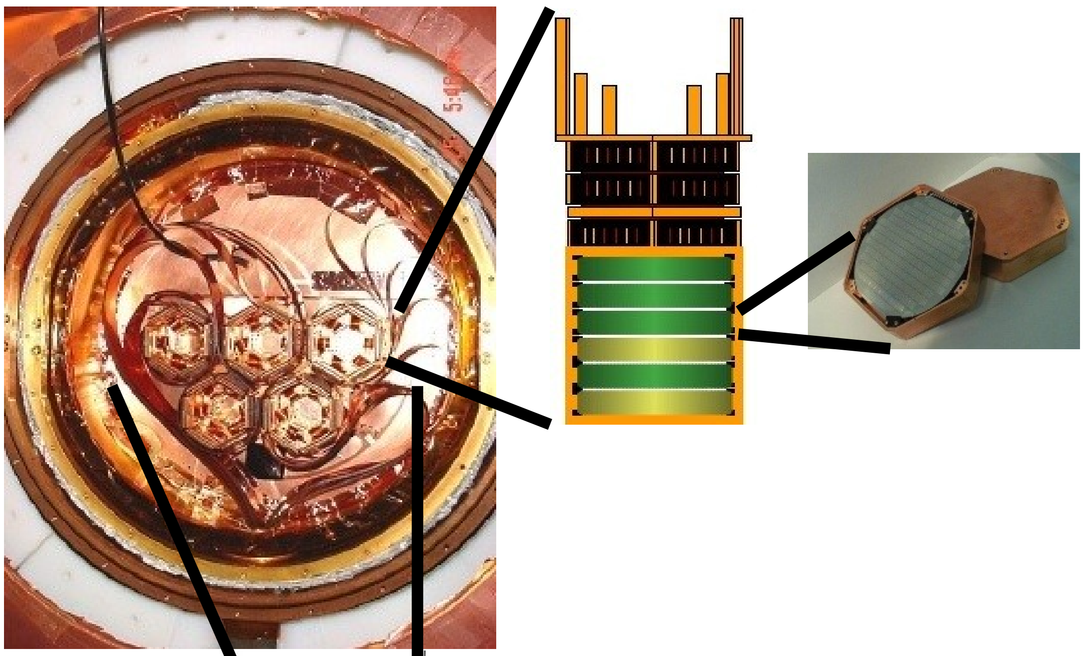
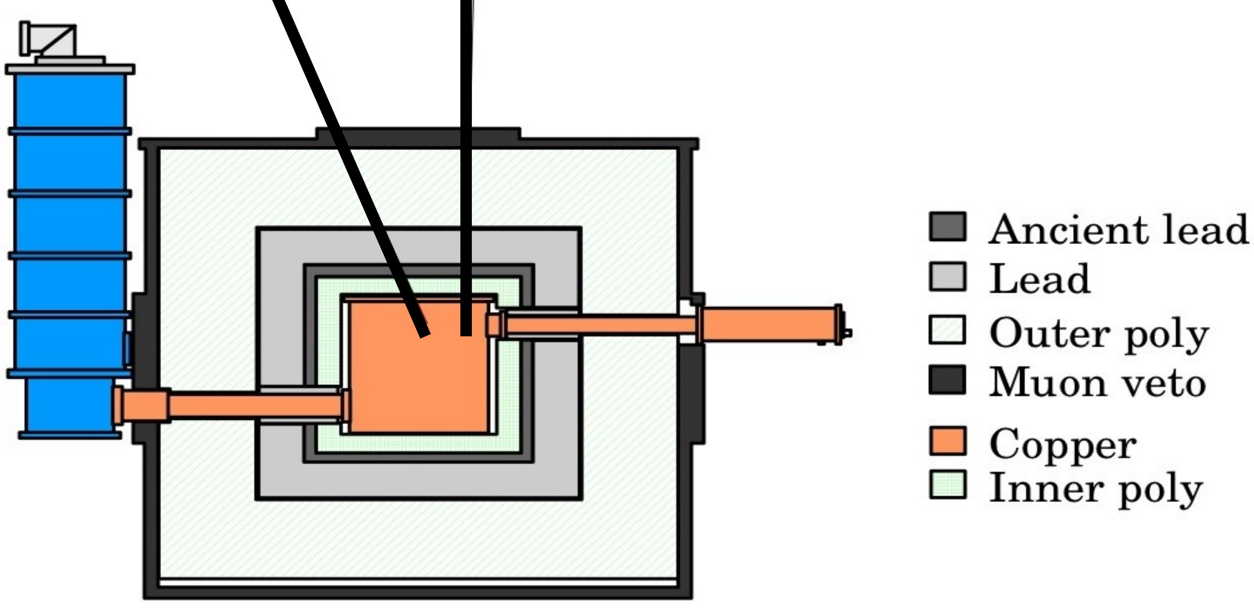
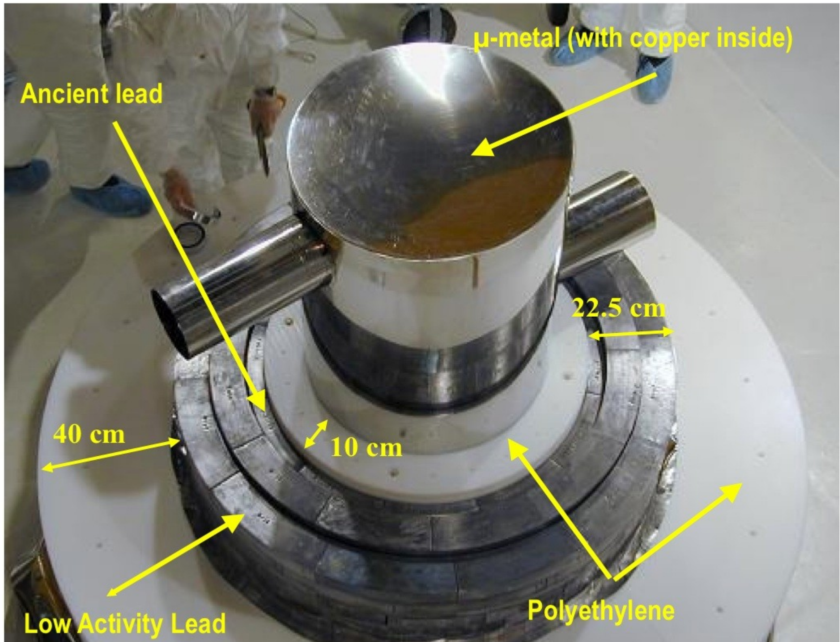
The CDMS setup & shielding



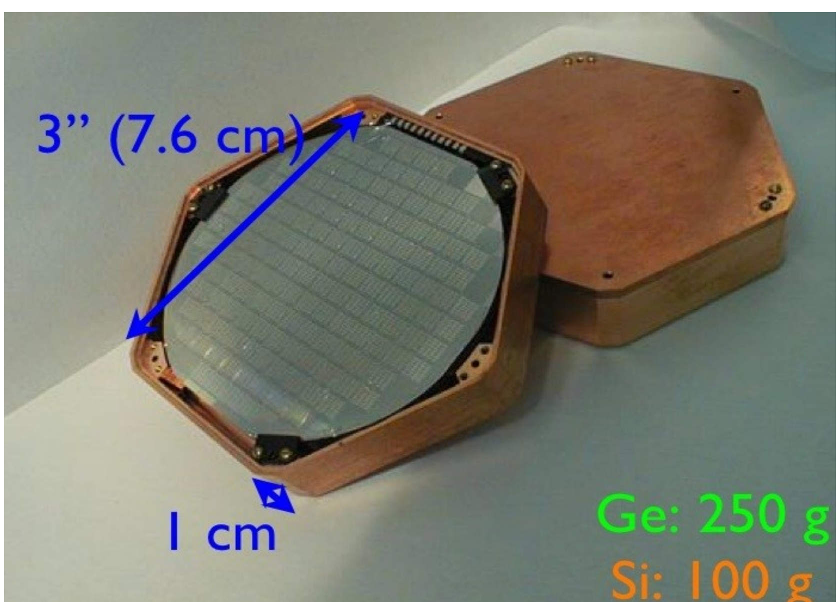
- 5 towers with 6 detectors each
- active veto against high energetic muons
- passive shielding:
  - lead against gammas from radioactive impurities
  - polyethylene to moderate neutrons from fission decays and from (α,n) interactions resulting from U/Th decays



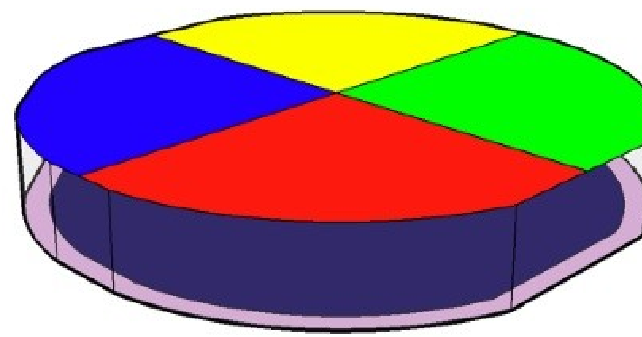


The CDMS ZIP detectors

- 19 Ge and 11 Si semiconductor detectors
- operated at cryogenic temperatures (~40 mK)
- 2 signals from interaction (ionization and phonon) → event by event discrimination between electron recoils and nuclear recoils
- z-sensitive readout
- xy-position imaging



Phonon readout:
4 quadrants of
phonon sensors



Charge readout:
2 concentric
electrodes

The ionization readout

- interaction creates electron hole pairs

  seperate using applied electric field

  collect charges on electrodes on surface

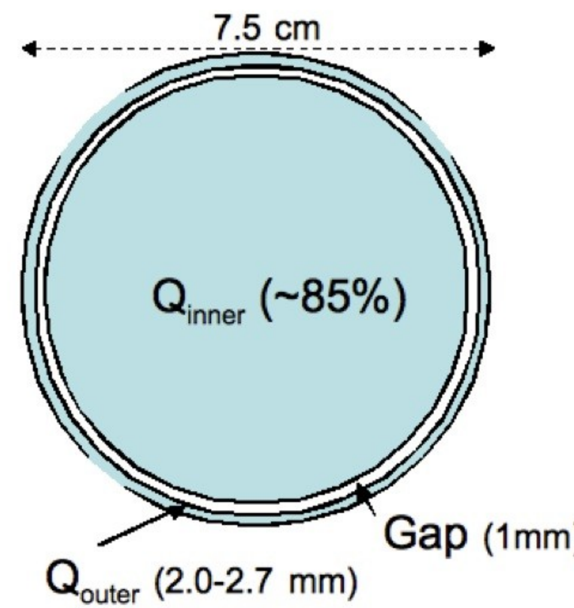
- drift field of 3 V/cm (4V/cm) on Ge (Si) detectors

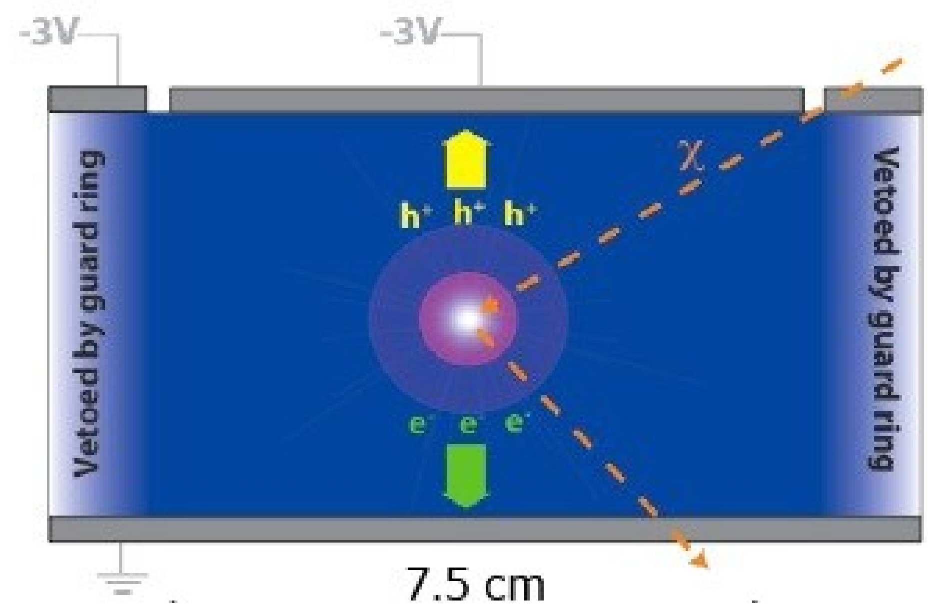
- interaction at crystal edges can have incomplete charge collection

  use outer electrode as guard ring

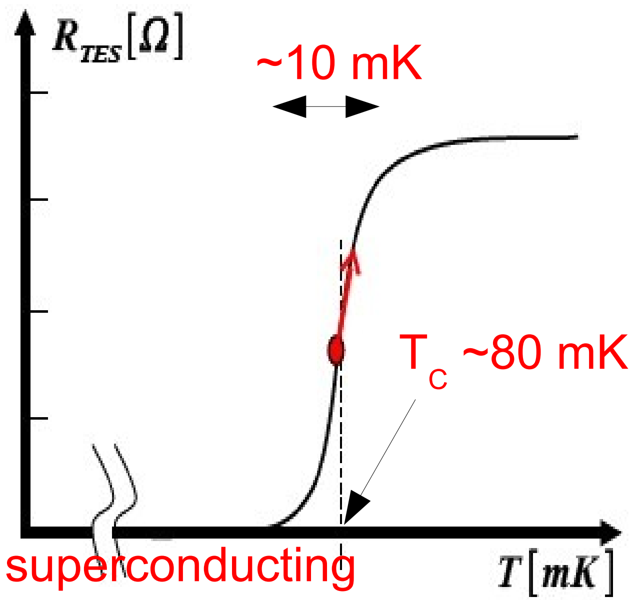
  omit qouter events

- low-energy resolution: 3-4%





The phonon readout

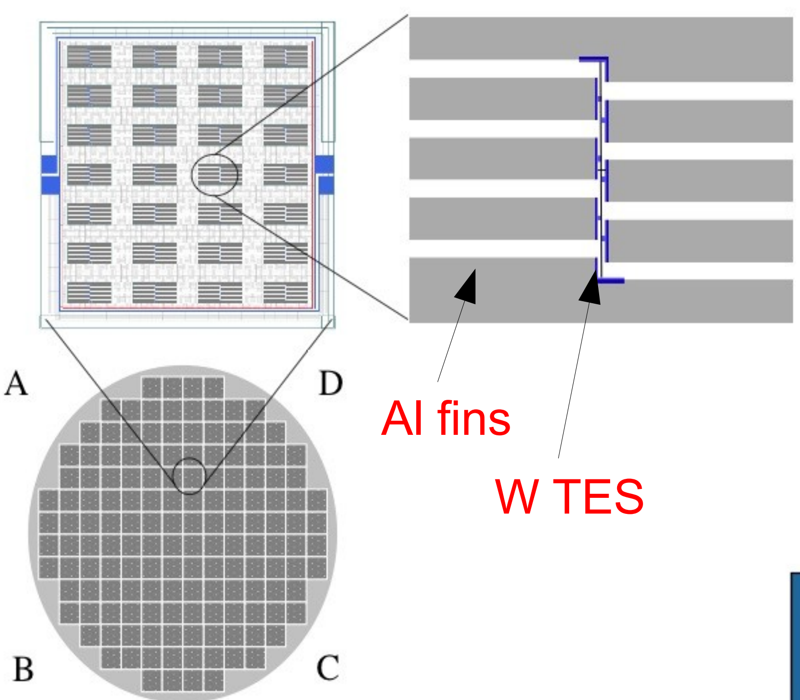


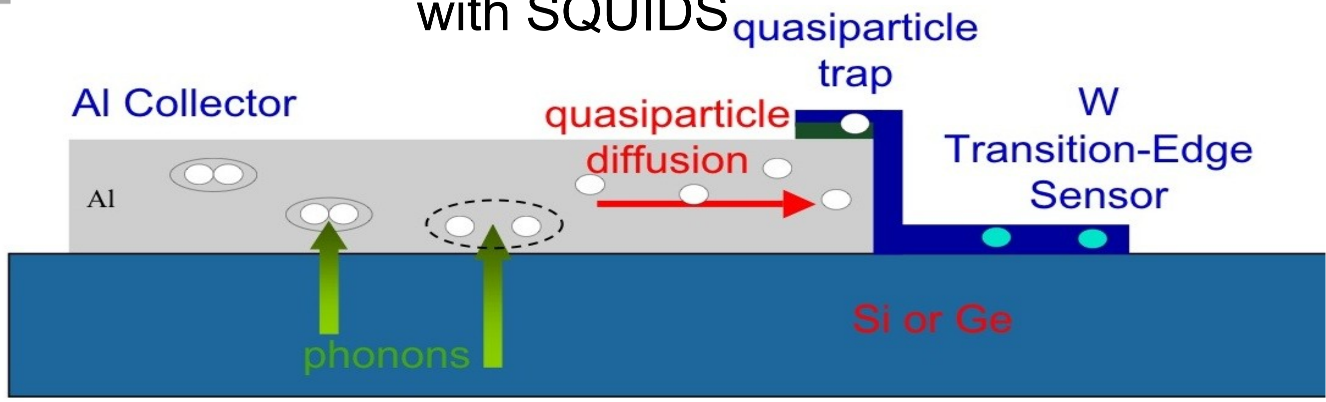
- segmented phonon readout (4 quadrants)
- each quadrant consists of 1036 tungsten TES (Transition Edge Sensors)
- fast response time ~5 μs
- low energy resolution: ~5%
- tungsten strips set just below the edge of superconductivity using bias voltage

energy deposition raises temperature

conductivity changes to normal

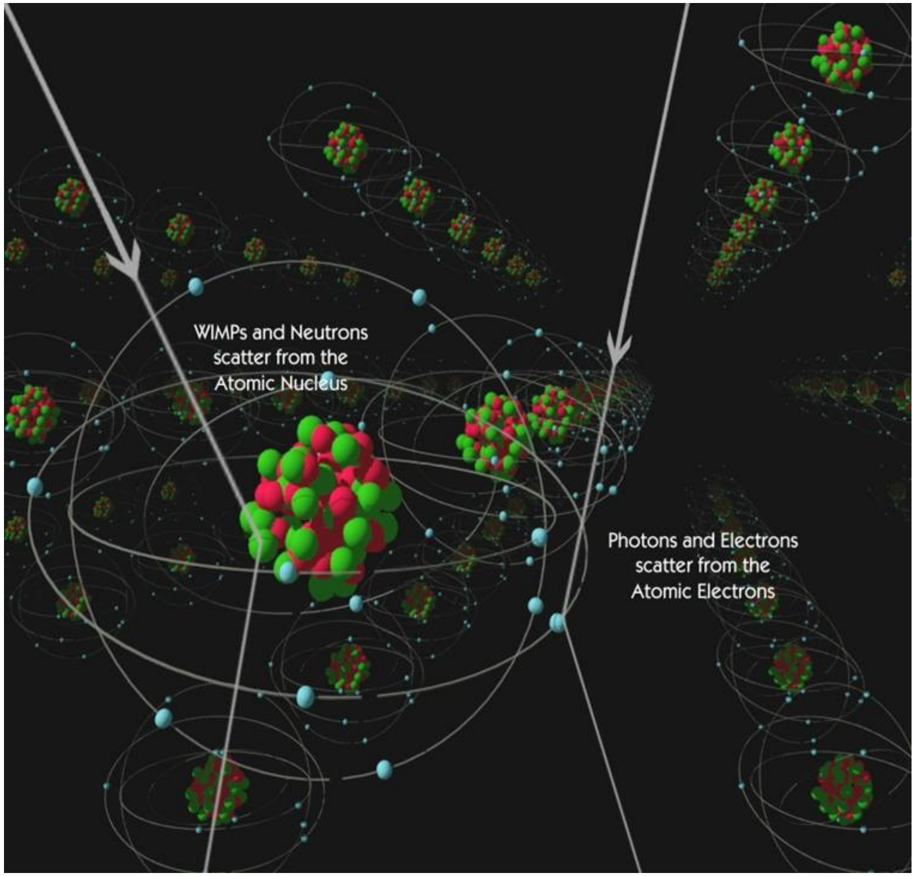
dramatic lowering of current read out with SQUIDS

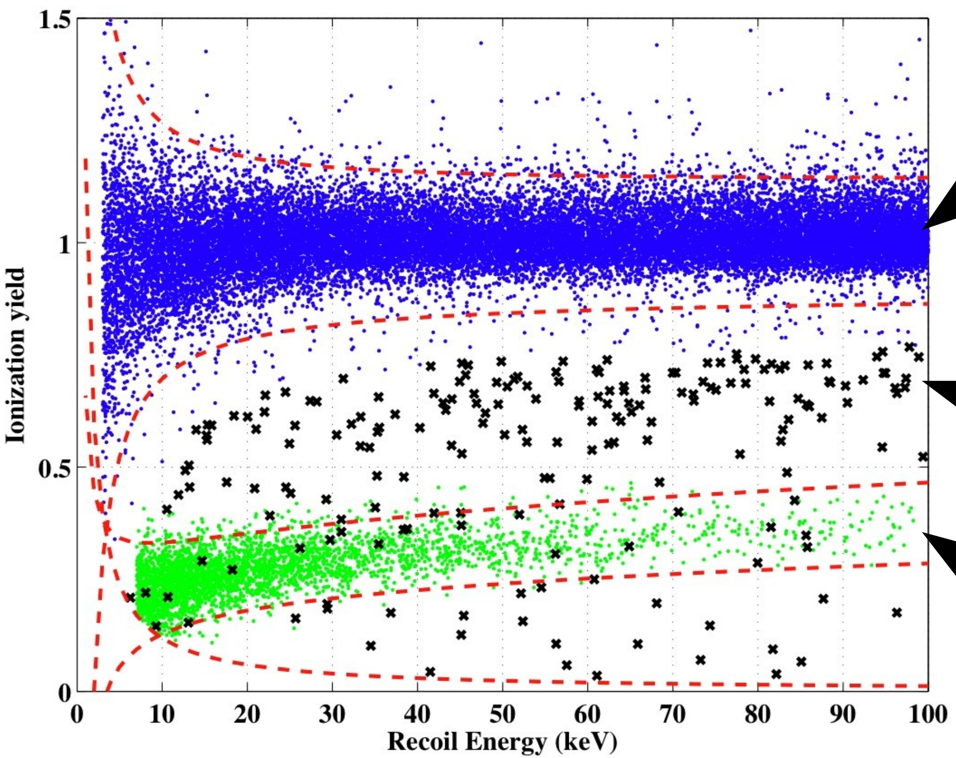




Primary background rejection

- most backgrounds (e, γ) produce electron recoils
- neutrons and WIMPs produce nuclear recoils which have a suppressed ionization signal
- define ionization yield as $y = \frac{E_{charge}}{E_{recoil}}$





electron recoils

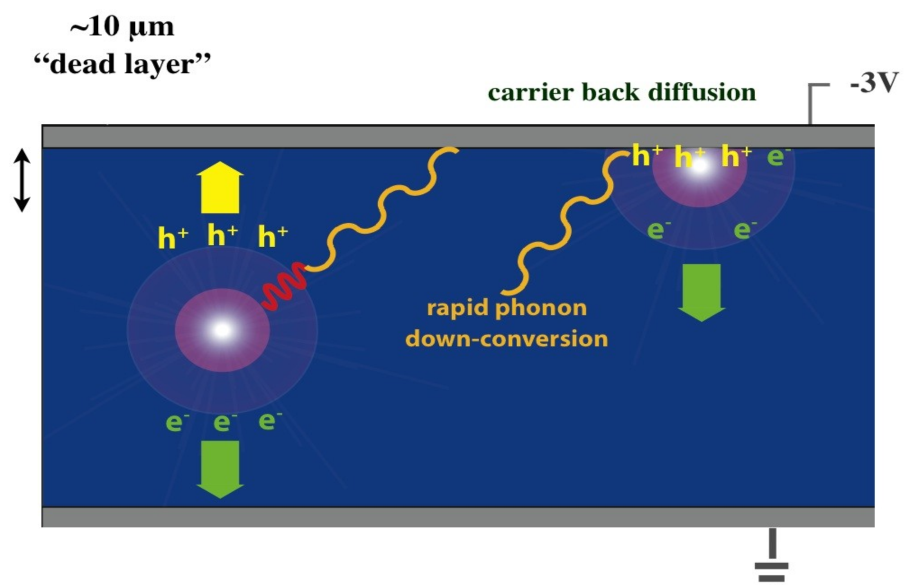
surface events

nuclear recoils

- better than 1:10000 rejection of electron recoils based on ionization yield alone
- dominant remaining background: low-yield surface events

Surface events and contamination

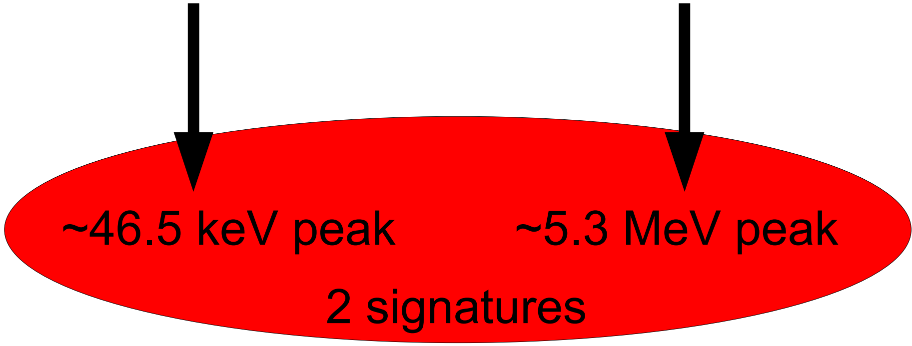
- reduced charge yield due to back-diffusion of charge carriers at the detector surface
- surface event background can be fully accounted for by two sources:
  1. low-energy electrons induced by the ambient photon flux from radioactive impurities in the experimental setup
  2. ^{210}Pb contamination of the detector surfaces



^{210}Pb contamination?

- detetctors are exposed to environmental Radon during fabrication, testing, ...
- ^{210}Pb is a decay product of ^{222}Rn and can be deposited on the detector surfaces
- decay chain:

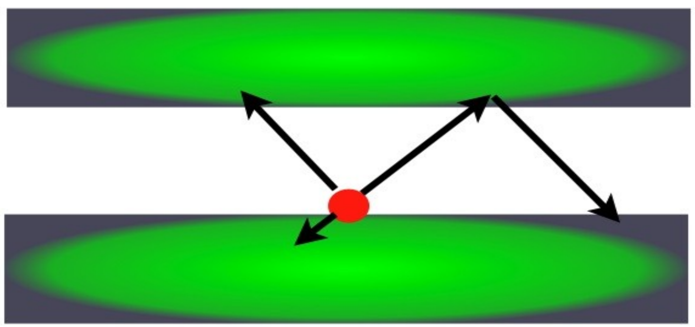
$$^{210}\mathrm{Pb} \xrightarrow[\beta]{22.3y} {}^{210}\mathrm{Bi} \xrightarrow[\beta]{5.0d} {}^{210}\mathrm{Po} \xrightarrow[\alpha]{138d} {}^{206}\mathrm{Pb}$$

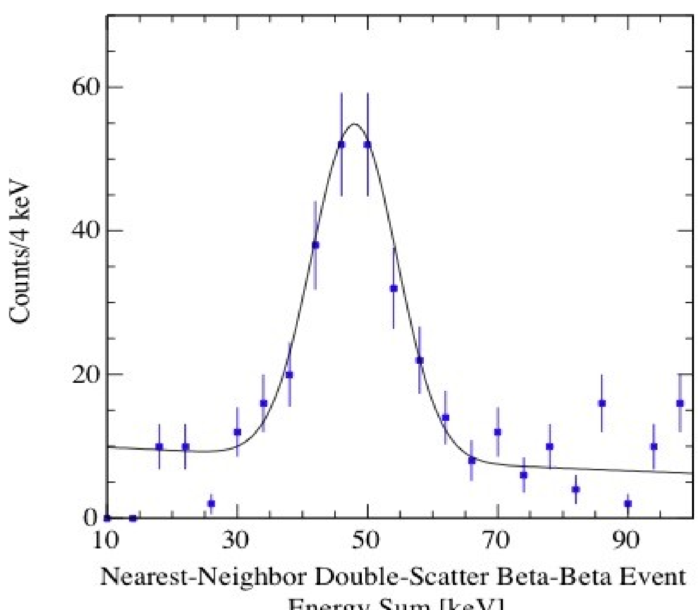


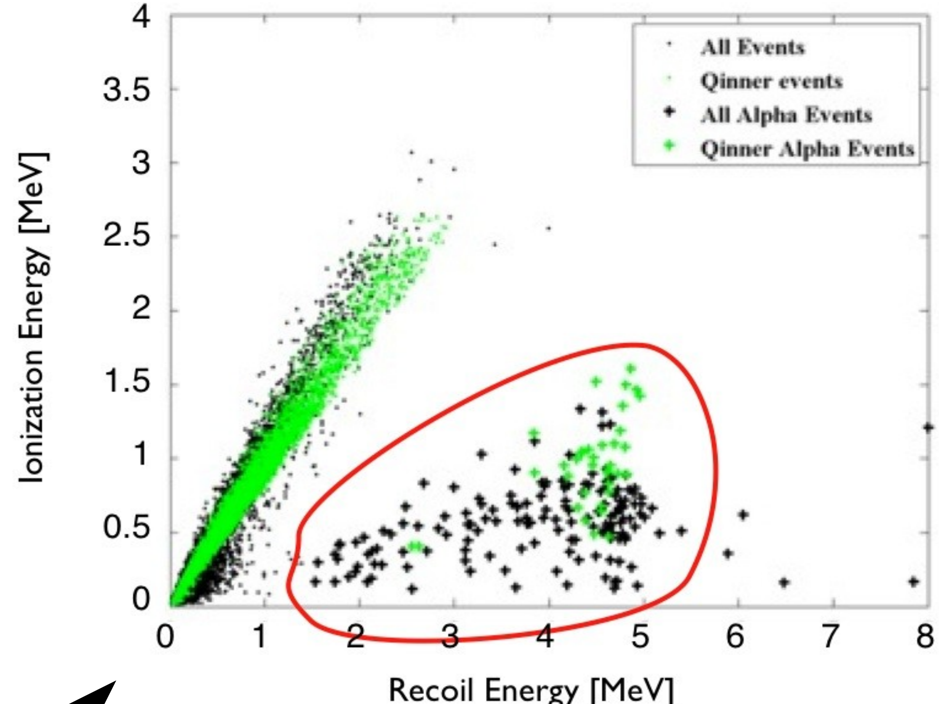
- significant reduction of this contribution for new towers (T3-T5)

Evidence for ^{210}Pb contamination

Sum over adjacent detectors (NND) to search for 46.5 keV peak!

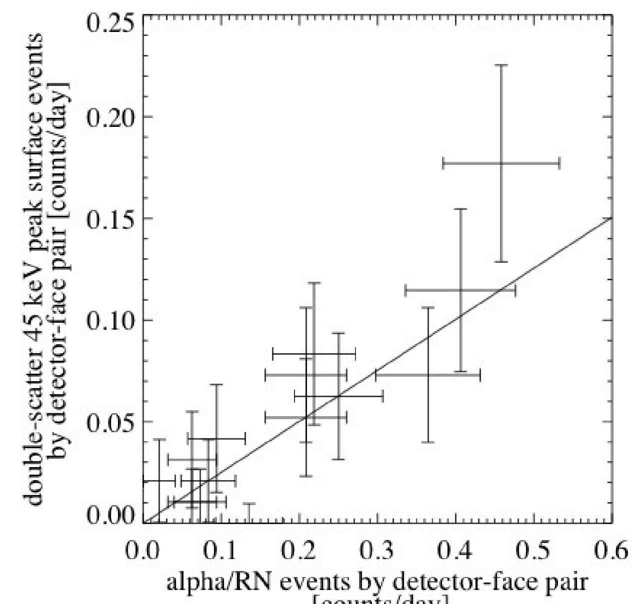






Check for low yield α's!

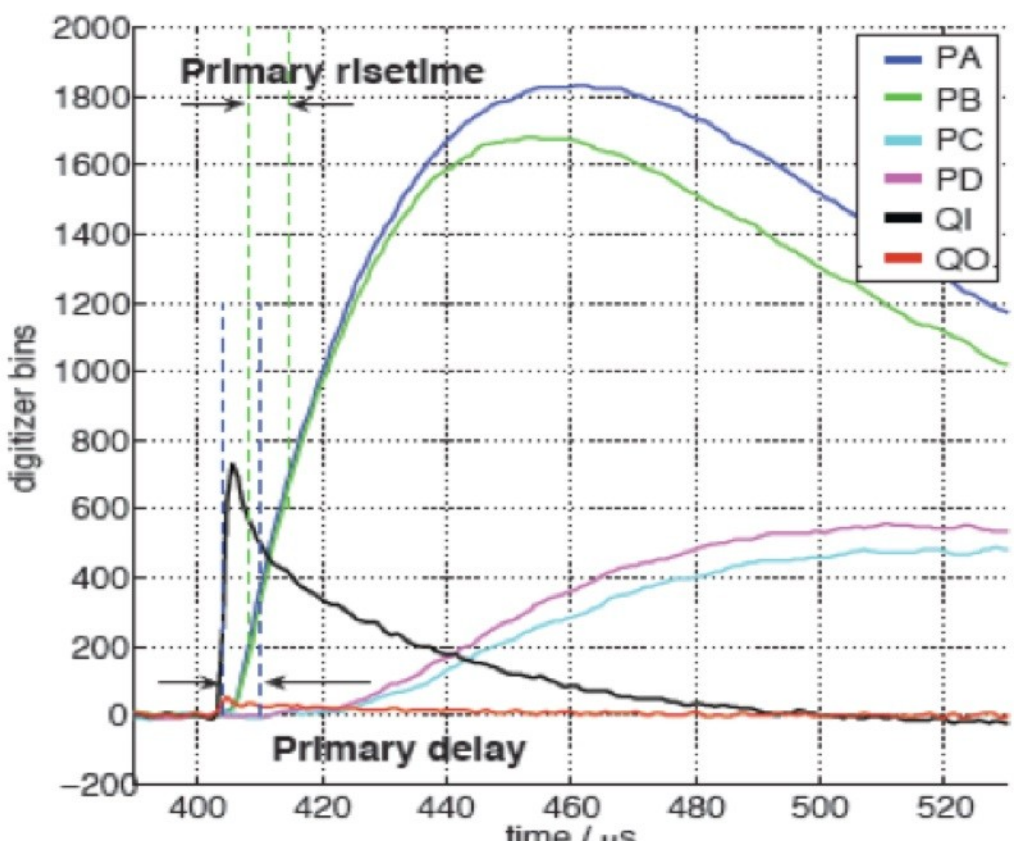
We see a strong correlation between both signatures.

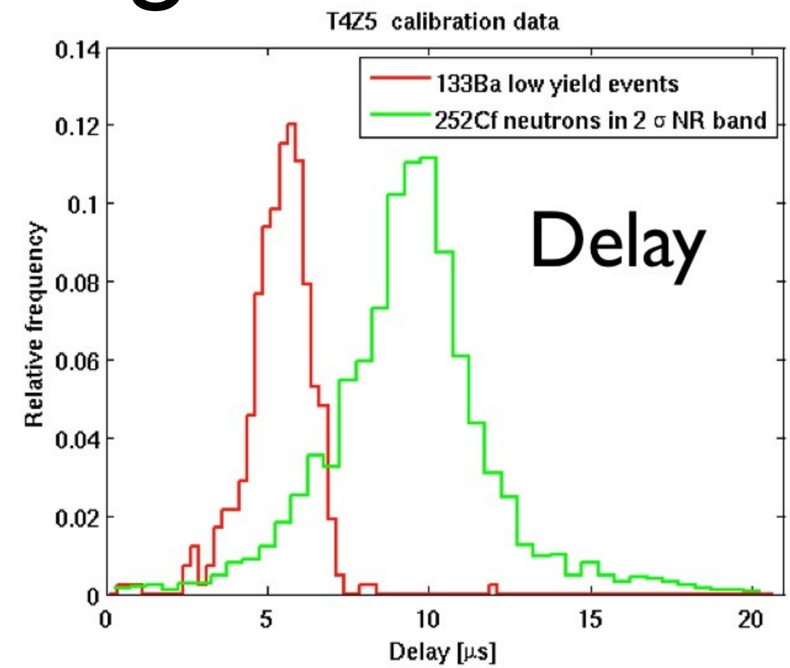


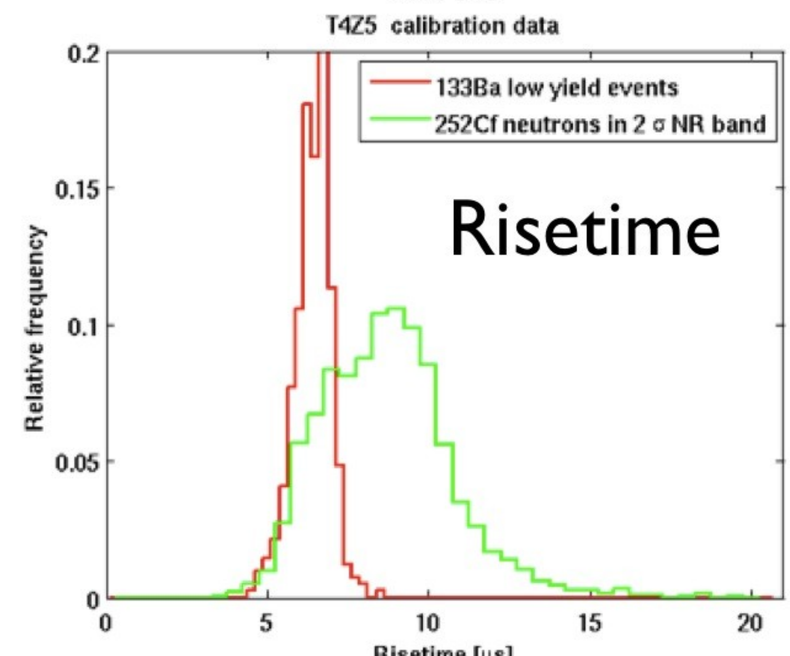
Phonon timing

Surface events are faster in timing than bulk nuclear recoils.

Use timing as discriminator to get rid of surface events.



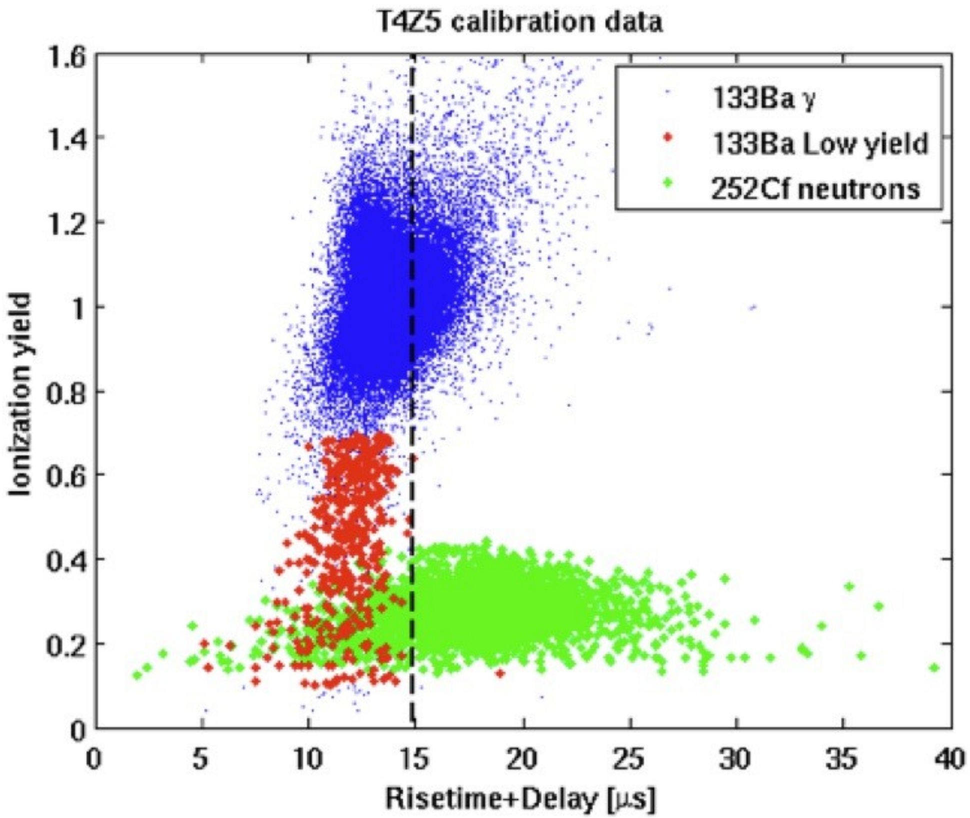


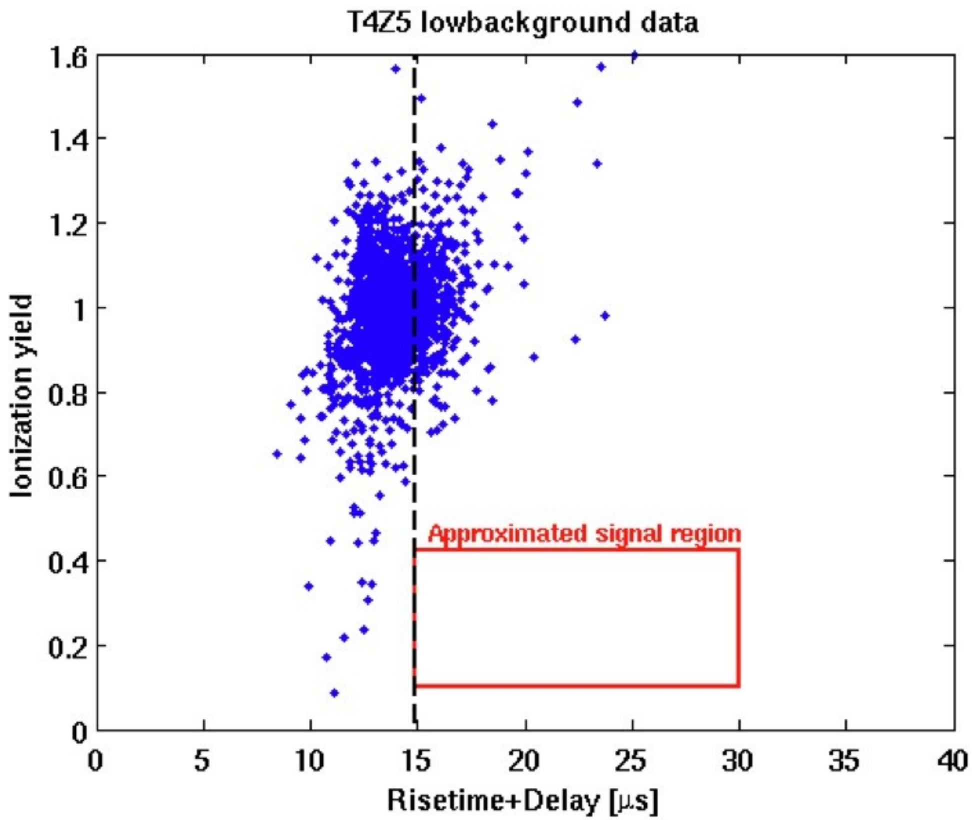


Surface event rejection - principle

- use risetime+delay to define timing cut on calibration data
- allow ~0.5 events total leakage within WIMP search data

- apply cut to lowbackground data
- surface event rejection ~200:1





Setting the timing cut

- estimate distribution of nuclear recoils from californium calibration data in each detector z→ nuclear recoil efficiency ϵ

- compute differential rate for WIMP mass of 60 GeV

spectrum averaged exposure $SAE_z(t_z)$

$$SAE = mT \frac{\int dE \frac{dR}{dE} \epsilon(E)}{\int dE \frac{dR}{dE}}$$

- estimate distribution of surface events from barium calibration data in each detector z→ leakage fraction

- apply correction factors for difference between barium and WIMP search data

- include estimated number of nuclear recoil single scatter

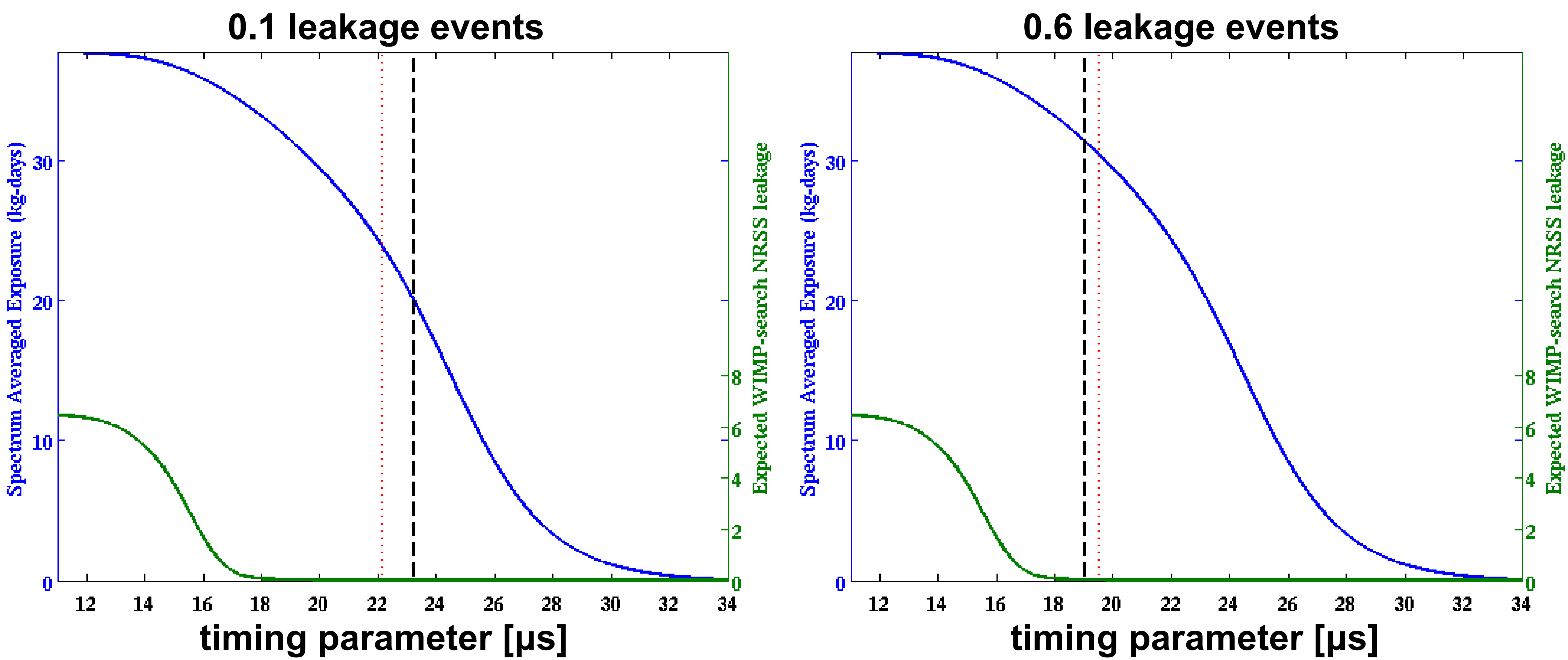
expected leakage $n_z(t_z)$

Minimize $$f(t) = \left(1 - \frac{\sum_z SAE_z(t_z)}{(\sum_z SAE_z)_{max}}\right)^2 + \left(1 - \frac{\sum_z n_z(t_z)}{(\sum_z n_z)_{target}}\right)^2$$

predefined leakage (try different values)

Setting the timing cut - example

- optimize trade-off between background and exposure
- take different timing performance of different detectors into account
- cut set in the tail of the barium distribution → Main difficulty!



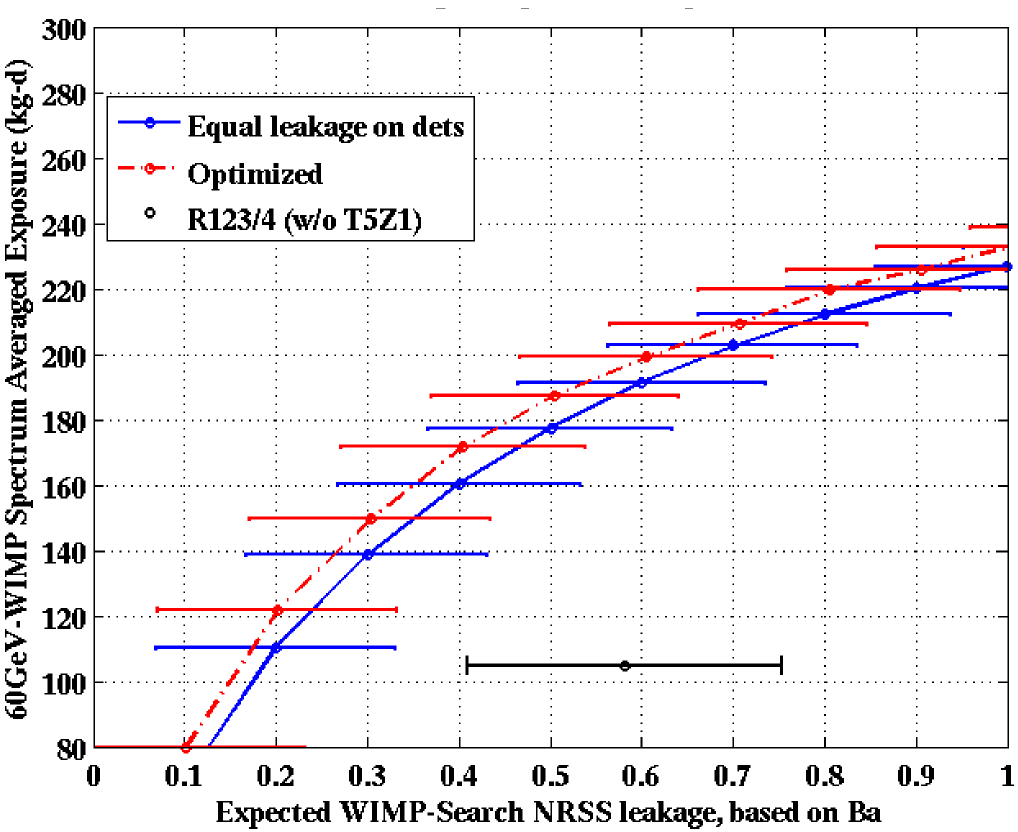
Which timing cut should we use?

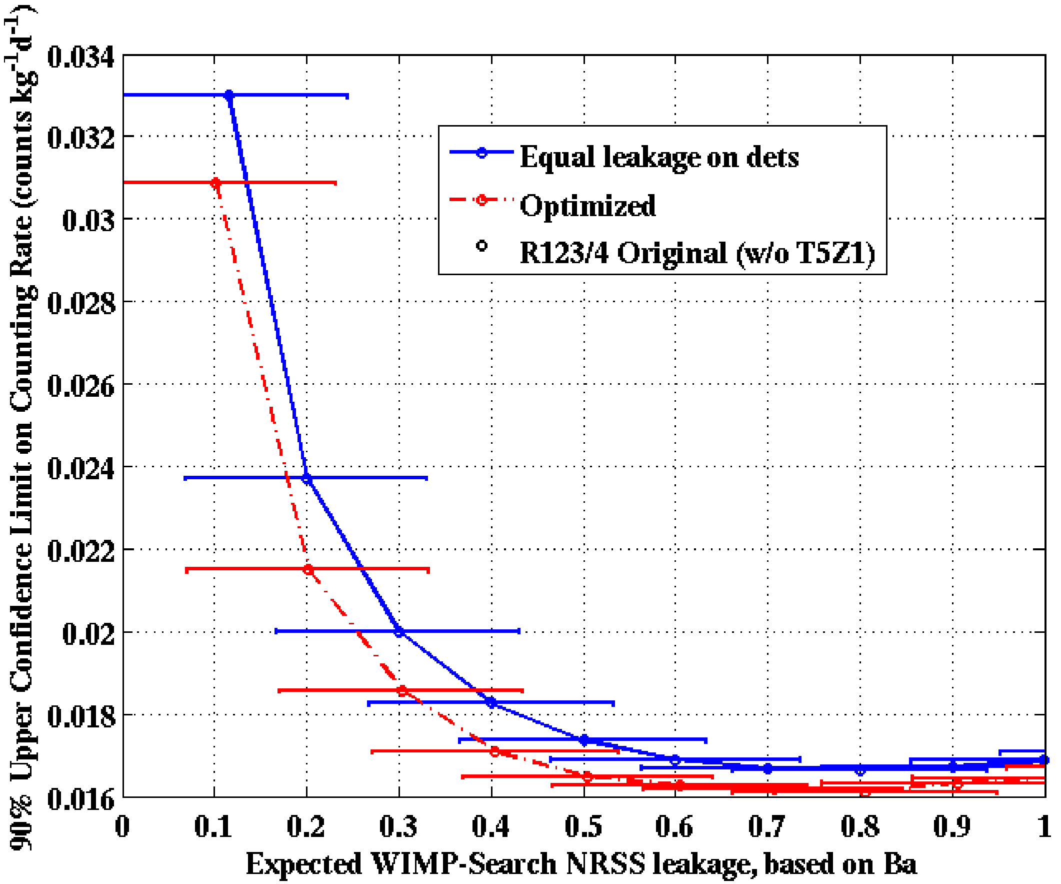
- gain ~10 kg-days exposure (SAE) with optimization
- compute sensitivity to estimate best cut position

Broad minimum around 0.7 leakage events.

Final cut set at 0.5 events!

But check on WIMP search data!



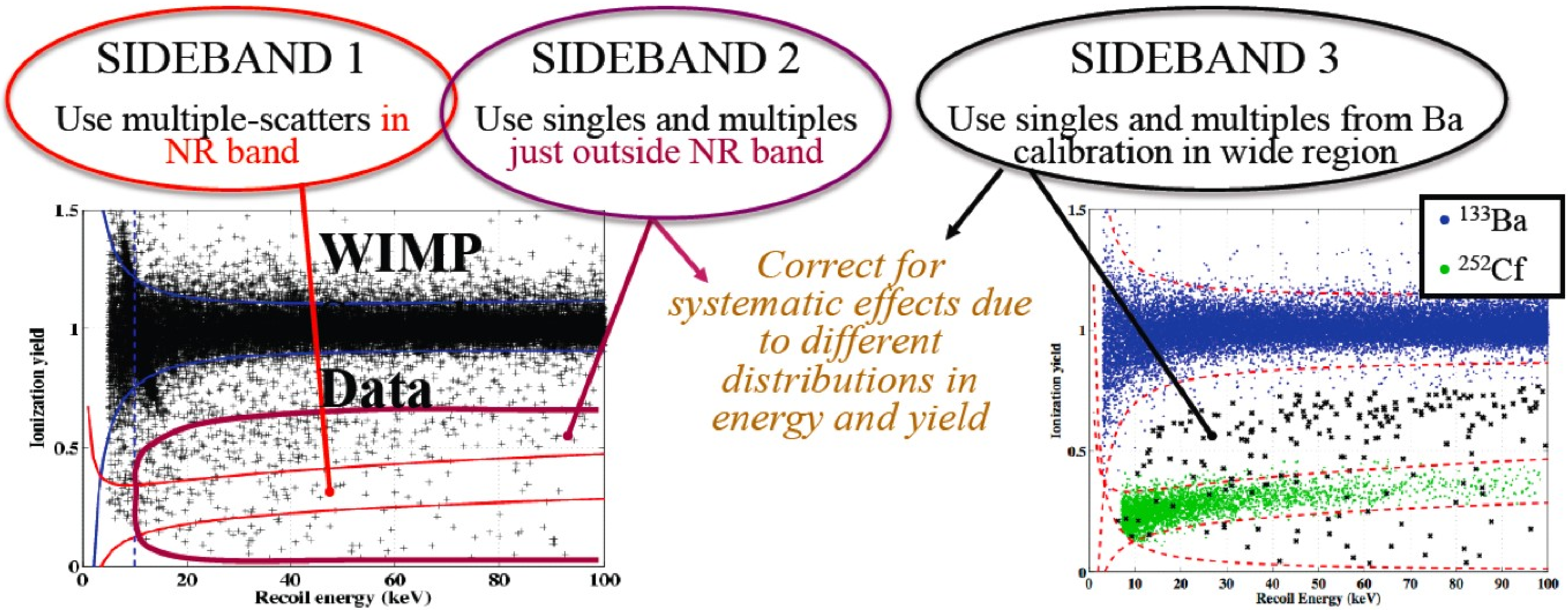


Surface event leakage estimate

- expected surface event leakage: $$\mu = \langle N^{fail}_{sing.} \rangle \cdot \frac{\langle N^{pass}_{mult.} \rangle}{\langle N^{fail}_{mult.} \rangle}$$

- use 3 independent event populations for estimating pass/fail-ratios

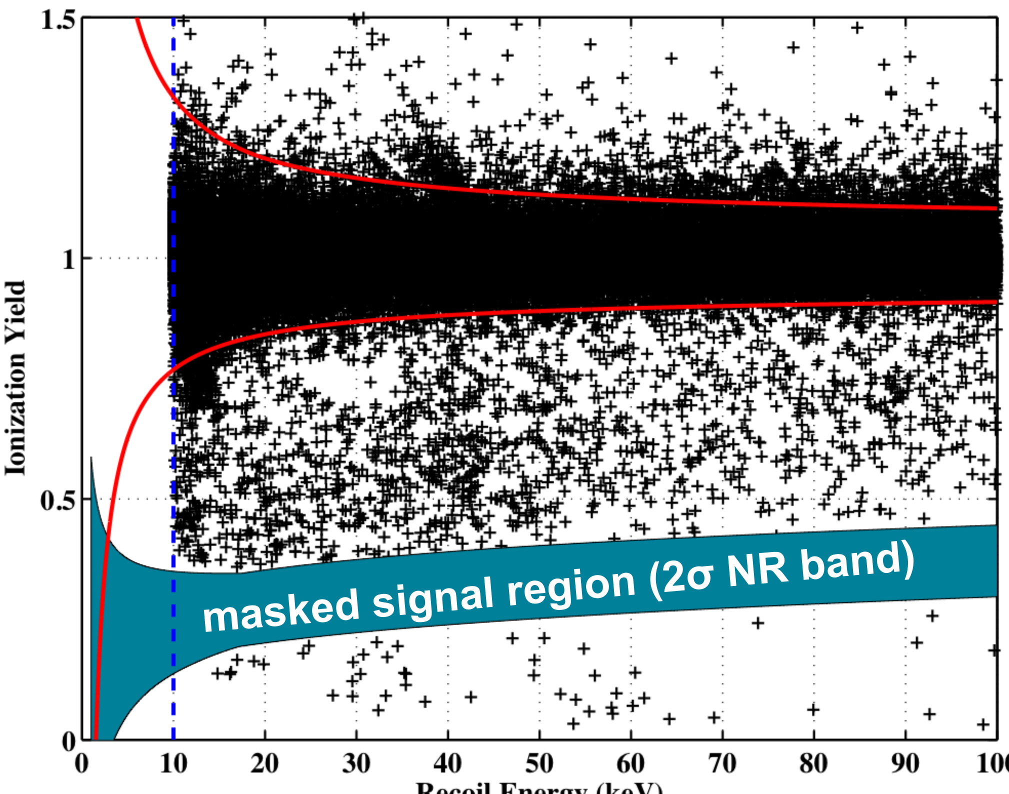
- all 3 are consistent → surface event leakage = 0.6 ± 0.1 (stat.) events

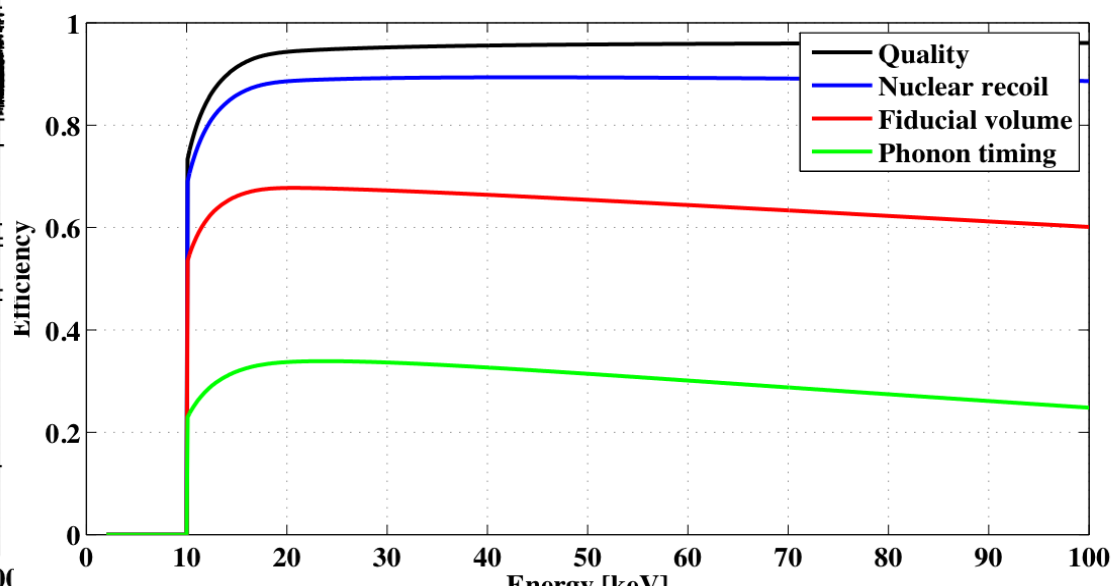


Analysis technique

Blind Analysis
Set all cuts and calculate efficiencies **before** looking at the signal region of the WIMP-search data.

Cut criteria for WIMP candidates:
- energy range: 10-100 keV
- data quality
- veto-anticoincidence
- single-scatters
- inside fiducial volume (qinner cut)
- inside 2σ nuclear recoil band
- no surface event (phonon timing)

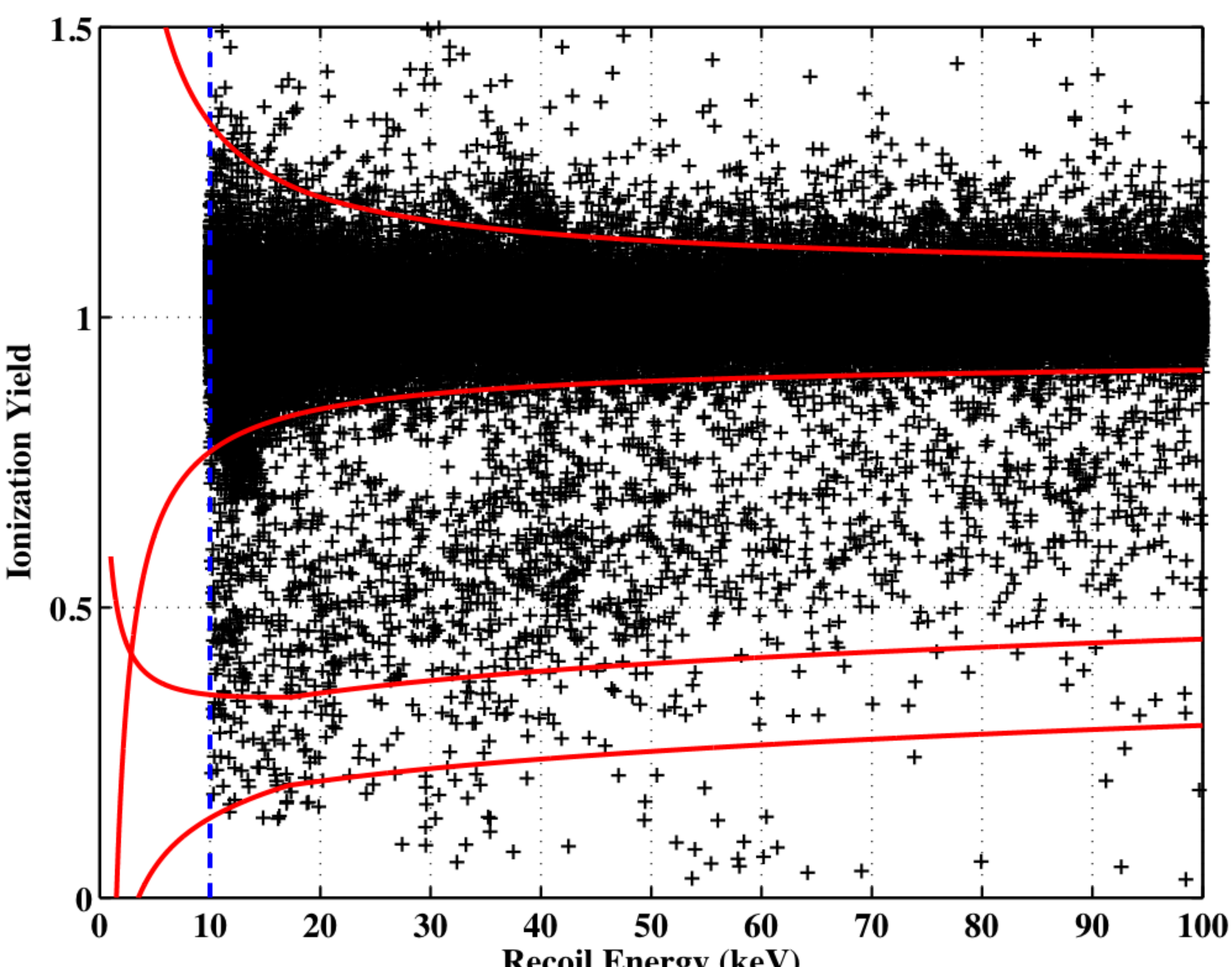




Analysis summary & unblinding

612.1 kg-days raw exposure

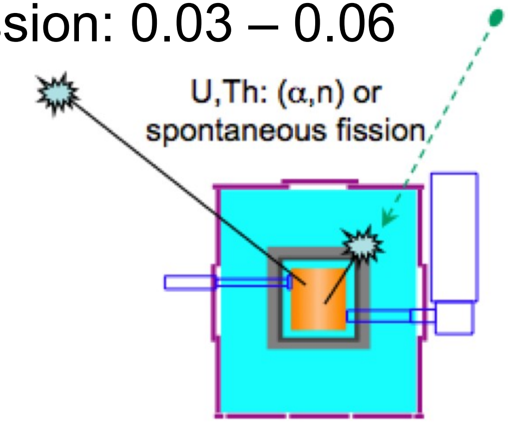
All WIMP search events **failing** the timing cut!



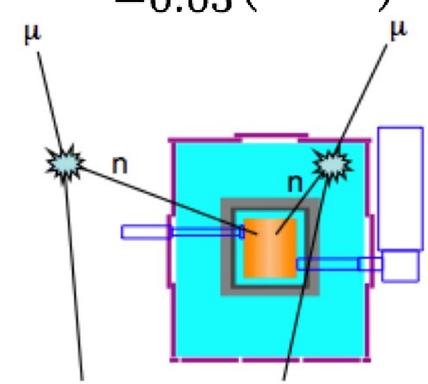
Background summary

- expected number of surface leakage events: 0.6 ± 0.1 (stat.)

- estimated neutron background: (α,n) & fission: 0.03 – 0.06



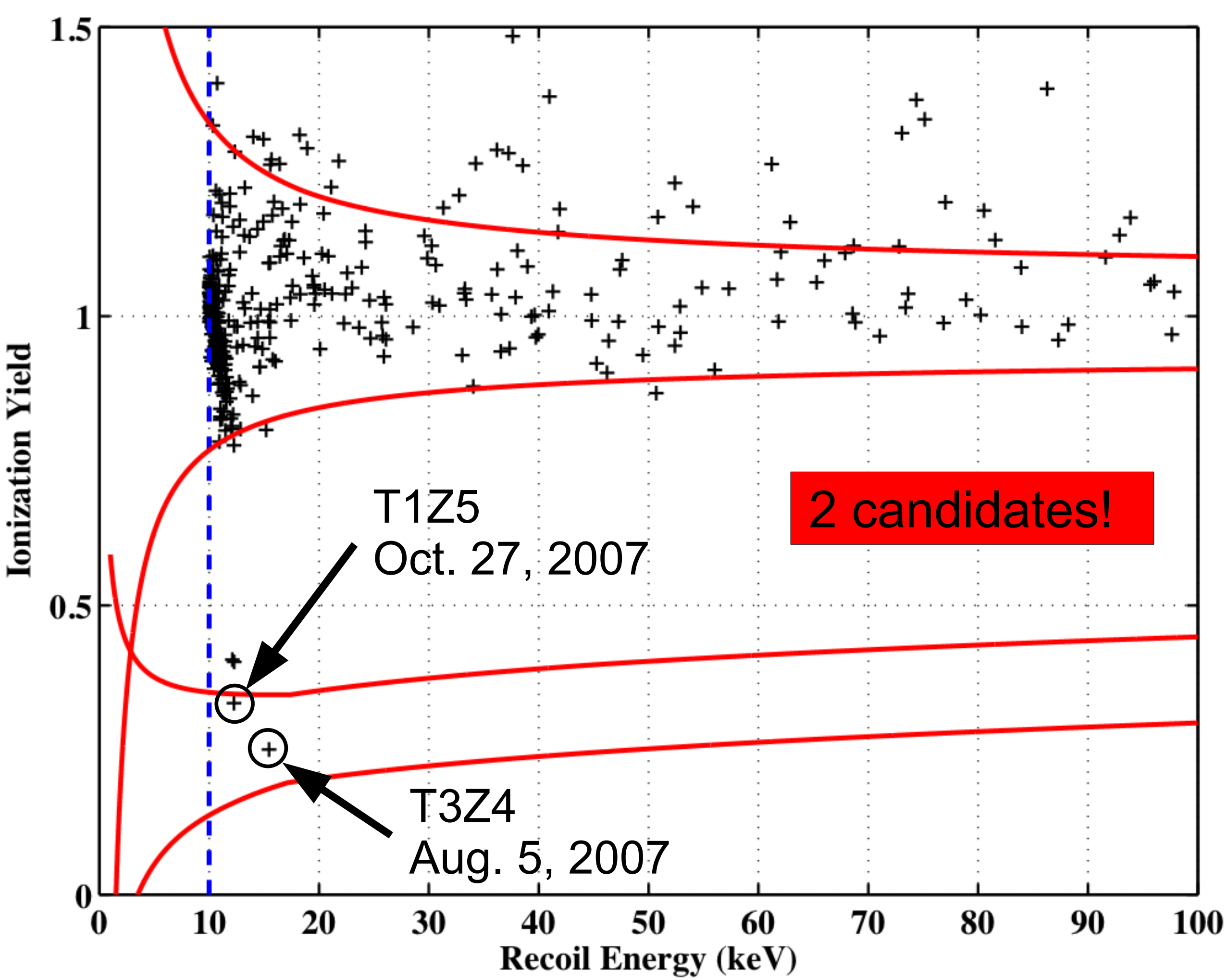
cosmogenic: $0.04^{+0.04}_{-0.03}(\mathrm{stat.})$



Analysis summary & unblinding

612.1 kg-days raw exposure

All WIMP search events **passing** the timing cut!



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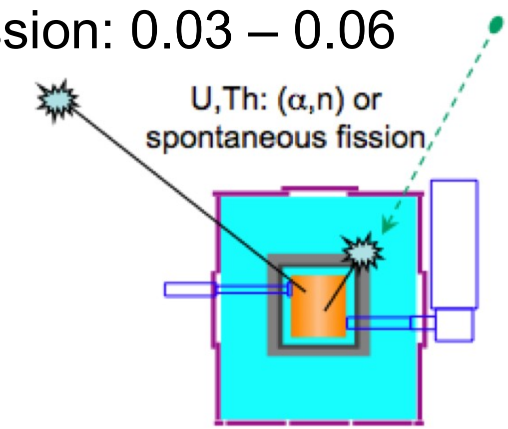

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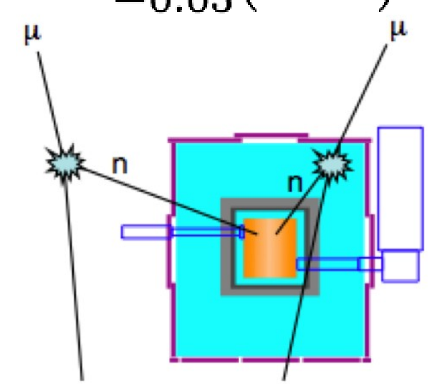
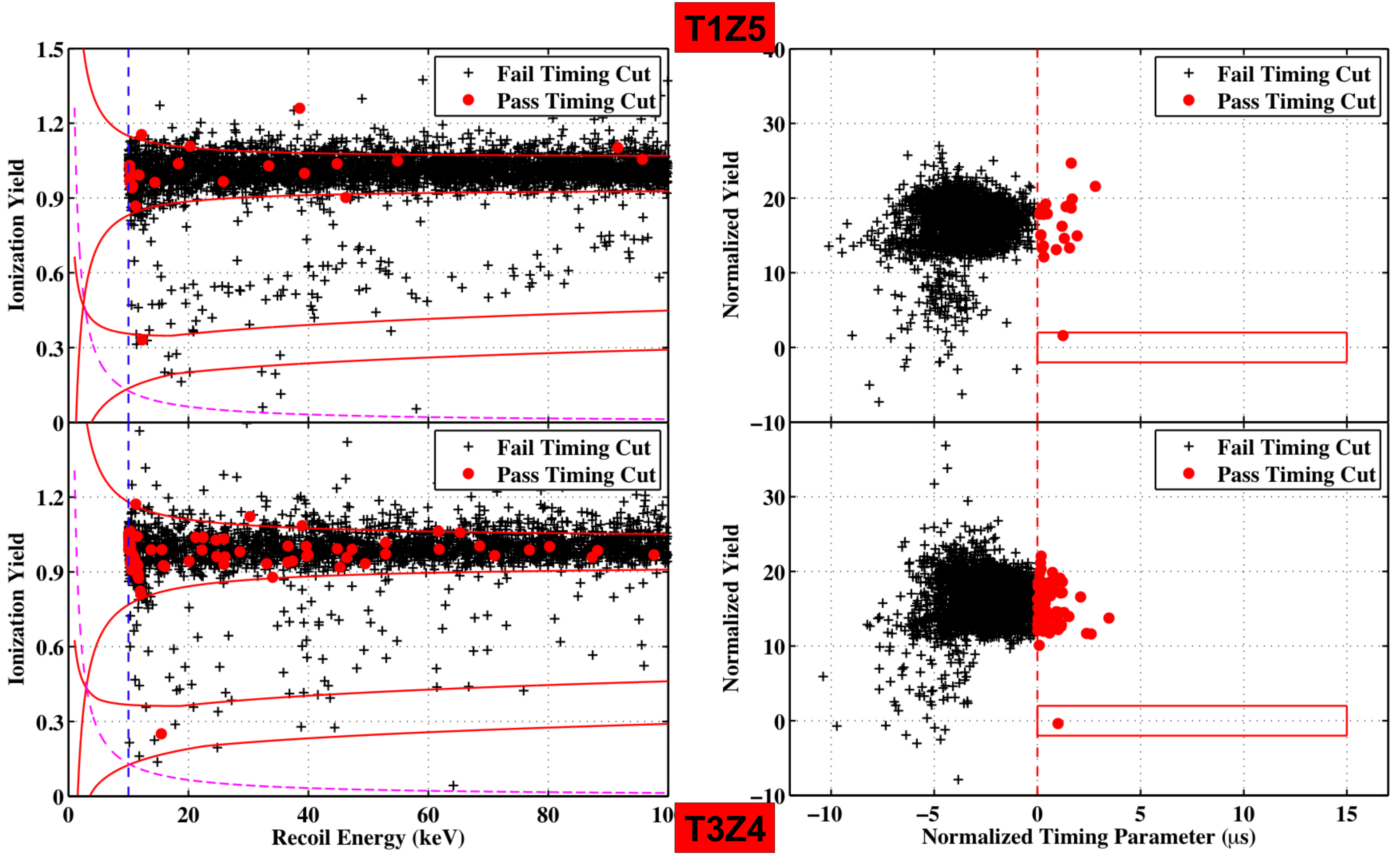


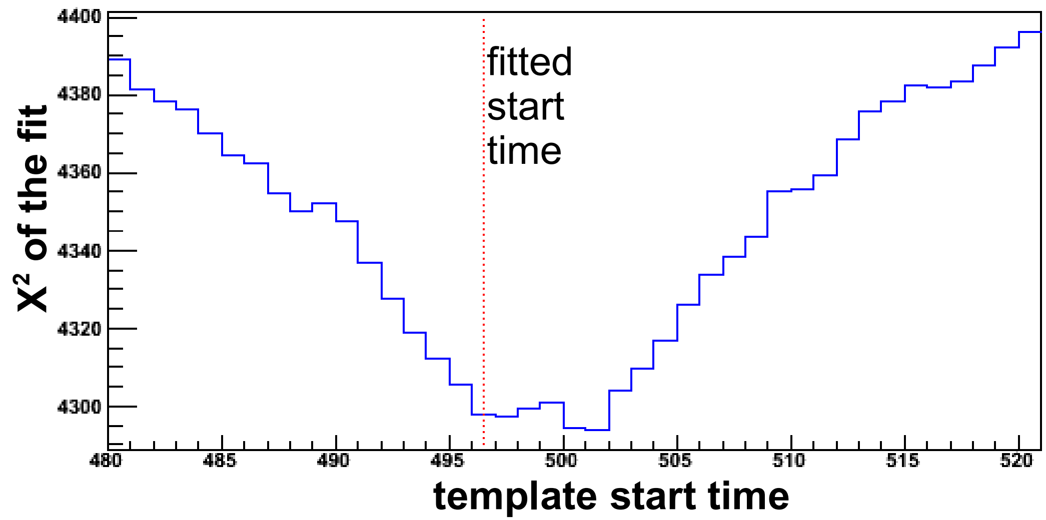
Closer look at the two events

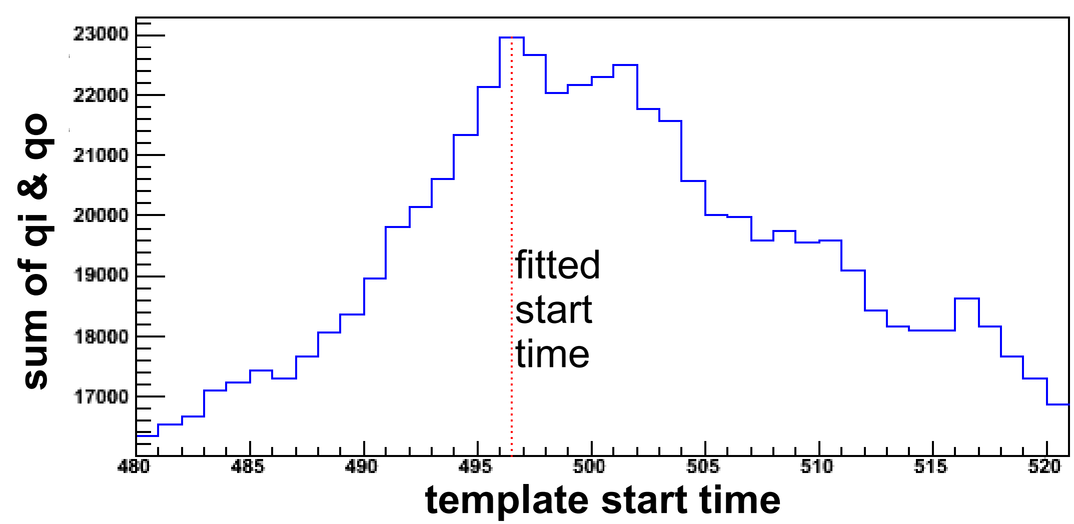


Reconstruction check

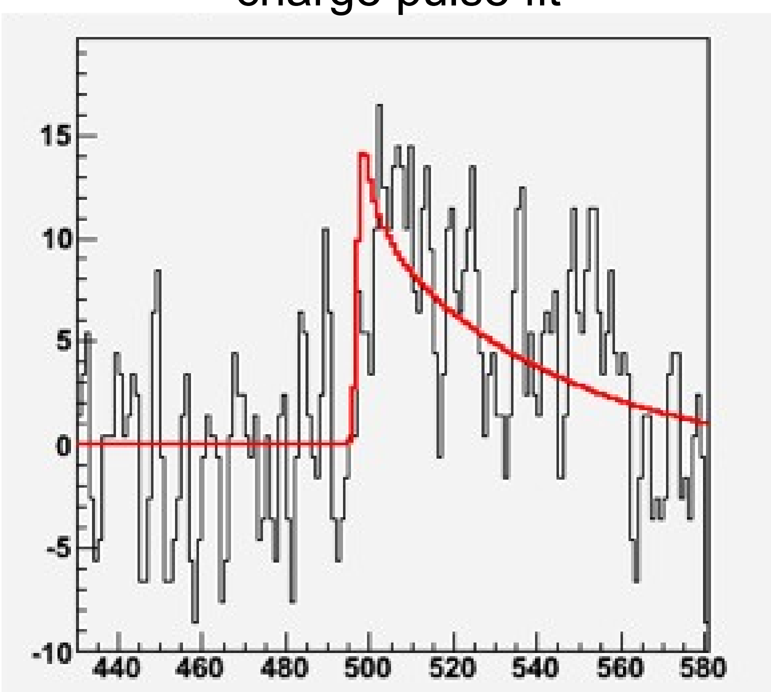
- possible problem with the determination of the charge pulse's start time of the candidate in T3Z4
- candidate in T1Z5 unaffected
- effects only ~1% of events with ionization energy < ~6 keV

Determining the start time of the charge pulse...



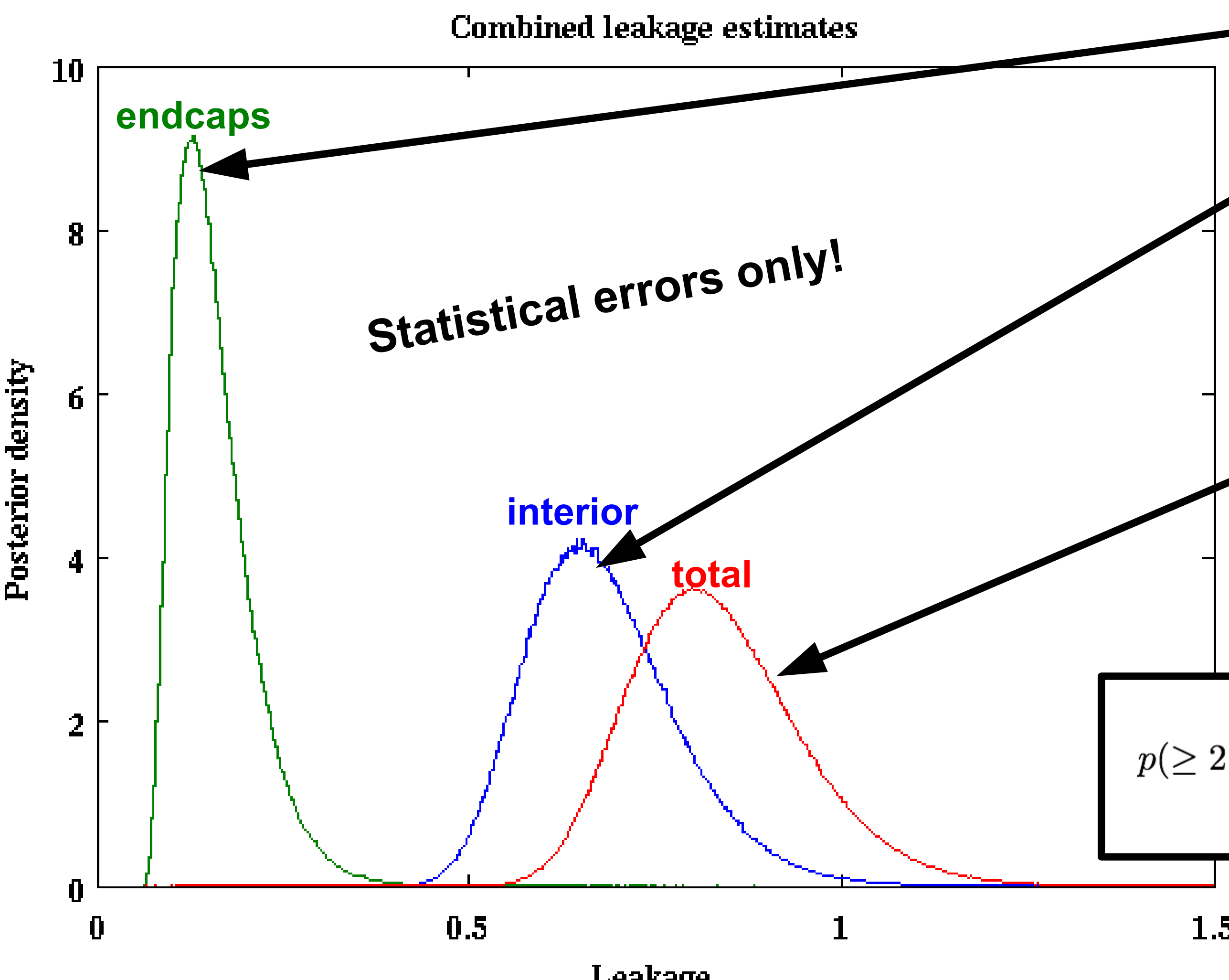


charge pulse fit



Revised surface event estimate

Compute a refined surface event leakage estimate accounting for additional leakage due to misidentified start times of the charge pulses!



$$n^{(ec)} = 0.16^{+0.06}_{-0.04}(stat)^{+0.05}_{-0.05}(syst)$$

$$n^{(int)} = 0.66^{+0.11}_{-0.09}(stat)^{+0.16}_{-0.15}(syst)$$

$$n^{(tot)} = 0.82^{+0.12}_{-0.10}(stat)^{+0.20}_{-0.19}(syst)$$

$$p(\geq 2 \text{ events}) = \int_0^\infty d\mu \; P(\mu) \cdot \sum_{k=2}^{\infty} \frac{e^{-\mu}\mu^k}{k!} = 23.3\%$$

(including systematic errors and neutron background)

Likelihood Analysis

We want to know how likely it is that the two candidates are electron recoils (ER) or nuclear recoils (NR)!

- estimate the probability distributions for both populations in the two detectors in which the events occured (T1Z5 & T3Z4)

- use three independent approaches:
  - 3D-KDE
    non-parameteric approach based on kernel density estimates (KDE) considering three quantities (energy, yield, timing [= delay + risetime])

  - 2D-λ
    parameteric approach using generalized lambda distributions considering two quantities (yield, timing [= delay + risetime])

  - 3D-λ
    parameteric approach using generalized lambda distributions considering three quantities (yield, delay, risetime)

- distinguish between both event classes using likelihood ratio $R = \log\left(\frac{f_{NR}}{f_{ER}}\right)$

Likelihood Analysis – results I

Take entire distributions into account!

This includes WIMP search single scatters **outside** of the acceptance region (in yield and timing)!

What is the probability of observing at least one surface electron event with a likelihood ratio greater than the candidate event in the respective detector?

	3D-KDE	2D-λ	3D-λ
T1Z5	24±5 %	12±2 %	12±2 %
T3Z4	4±2 %	5±1 %	5±1 %

→ Encourages suspicion that the event in T1Z5 is a surface event!

Likelihood Analysis – results II

Look just at events **inside** the acceptance region!

This “compares“ nuclear recoils **not** to all surface events but **only** to surface events **leaking** into the acceptance region!

What is the probability of a true **nuclear** recoil within the acceptance region to have a likelihood ratio **smaller** than the candidate event in the respective detector?

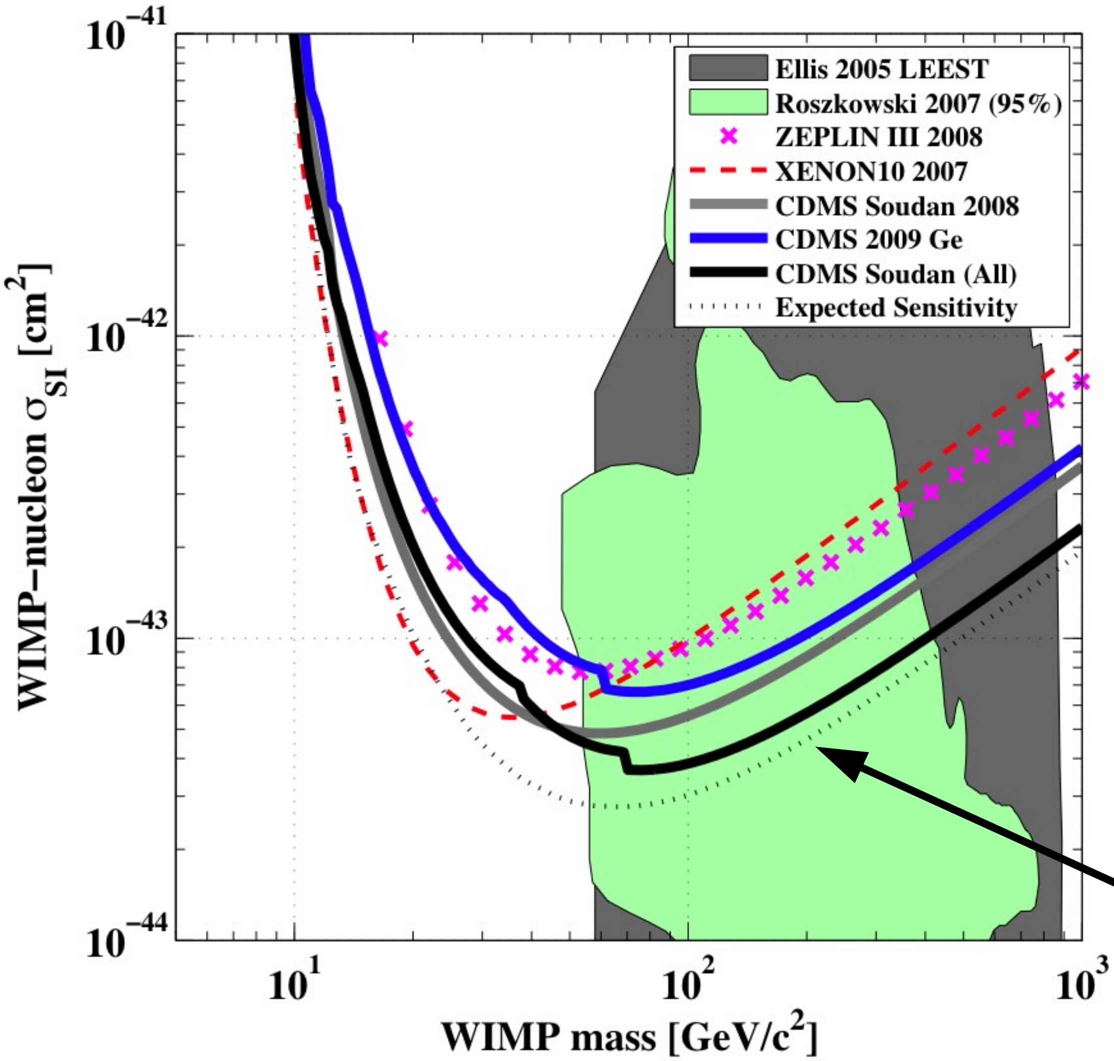
	3D-KDE	3D-λ
T1Z5	1 %	3 %
T3Z4	12 %	2 %

What is the probability of a true **electron** recoil within the acceptance region to have a likelihood ratio **greater** than the candidate event in the respective detector?

	3D-KDE	3D-λ
T1Z5	83 %	28 %
T3Z4	55 %	34 %

→ Encourages suspicion that the event in T1Z5 is a surface event!

Spin-independent cross section limit



- two candidate events at 12.3 keV and 15.5 keV

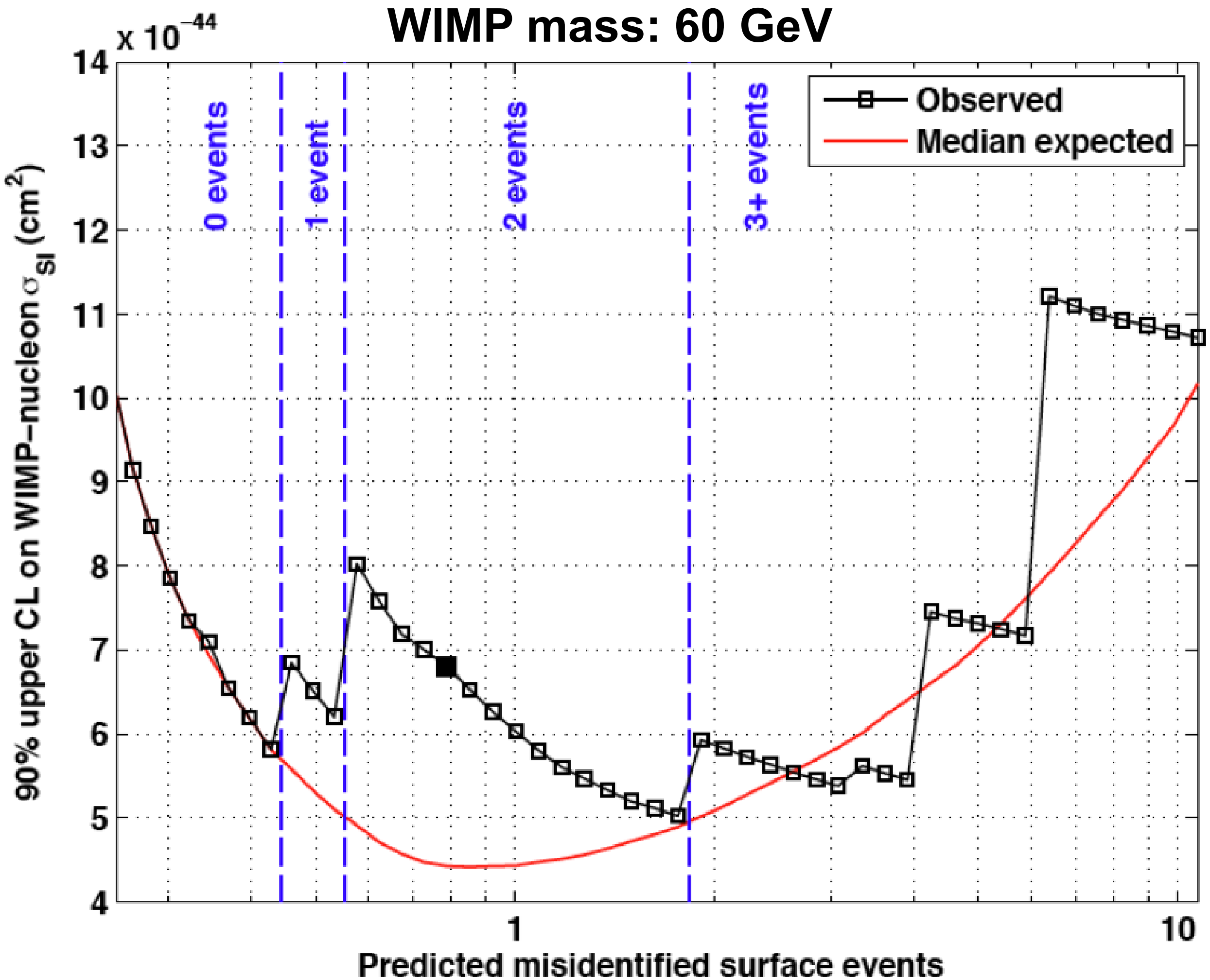
- compute limit using optimum interval method without background subtraction

- upper limit on the WIMP-nucleon cross section @ 70 GeV: $\sigma = 3.8 \cdot 10^{-44}$ cm² (combined with previous data taken in Soudan)

sensitivity based on total background estimate (surface events & neutron background)

World leading 90% C.L. upper limit on scalar interaction cross sections for WIMP masses above ~70 GeV!

Varying the timing cut



- Both candidates are removed by setting the timing cut to 0.4 leakage events. However, the exposure would be reduced by 28%.

- No additional events would enter the signal region until the timing cut is loosened to an estimated surface event leakage of 1.7 events.

- The dependence of the cross section limit on the actual timing cut setting is rather weak.

First constraints on IDM from CDMS

- Inelastic dark matter (IDM) scenario has been invoked to explain the discrepancy between the DAMA/LIBRA claim and results from other experiments.

- WIMP-nucleus scattering occurs through transition of WIMP into excited state

- Excluded regions are defined by demanding the upper limit on the cross section to completely rule out the DAMA/LIBRA allowed cross section intervals at a given WIMP mass and mass splitting.

- used paramters are important:

  escape velocity:

  v_{esc} = 544 km/s

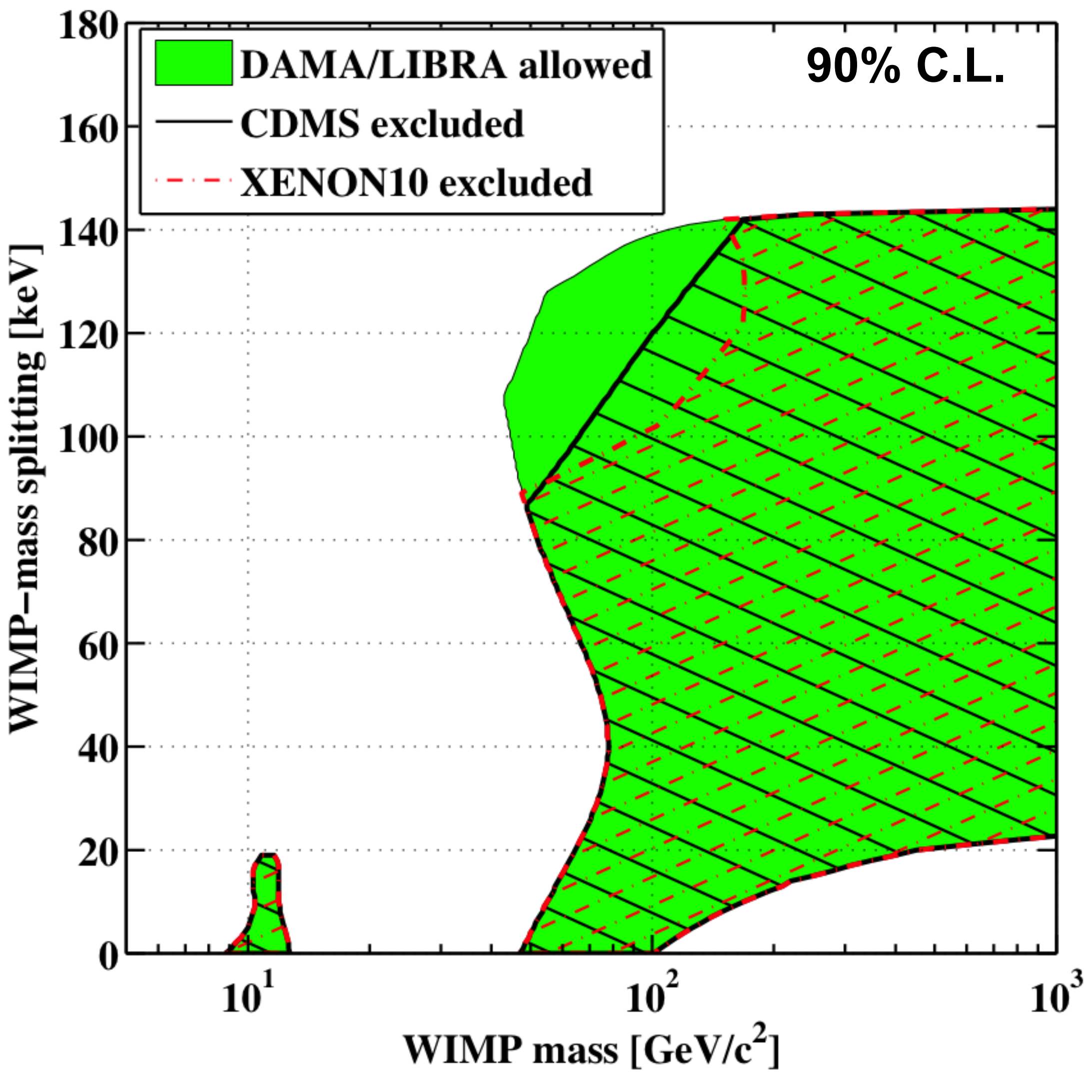
  DAMA quenching factors:

  q_I = 0.09

  q_{Na} = 0.30

  XENON10 scintillation efficiency:

  L_{eff} = 0.19

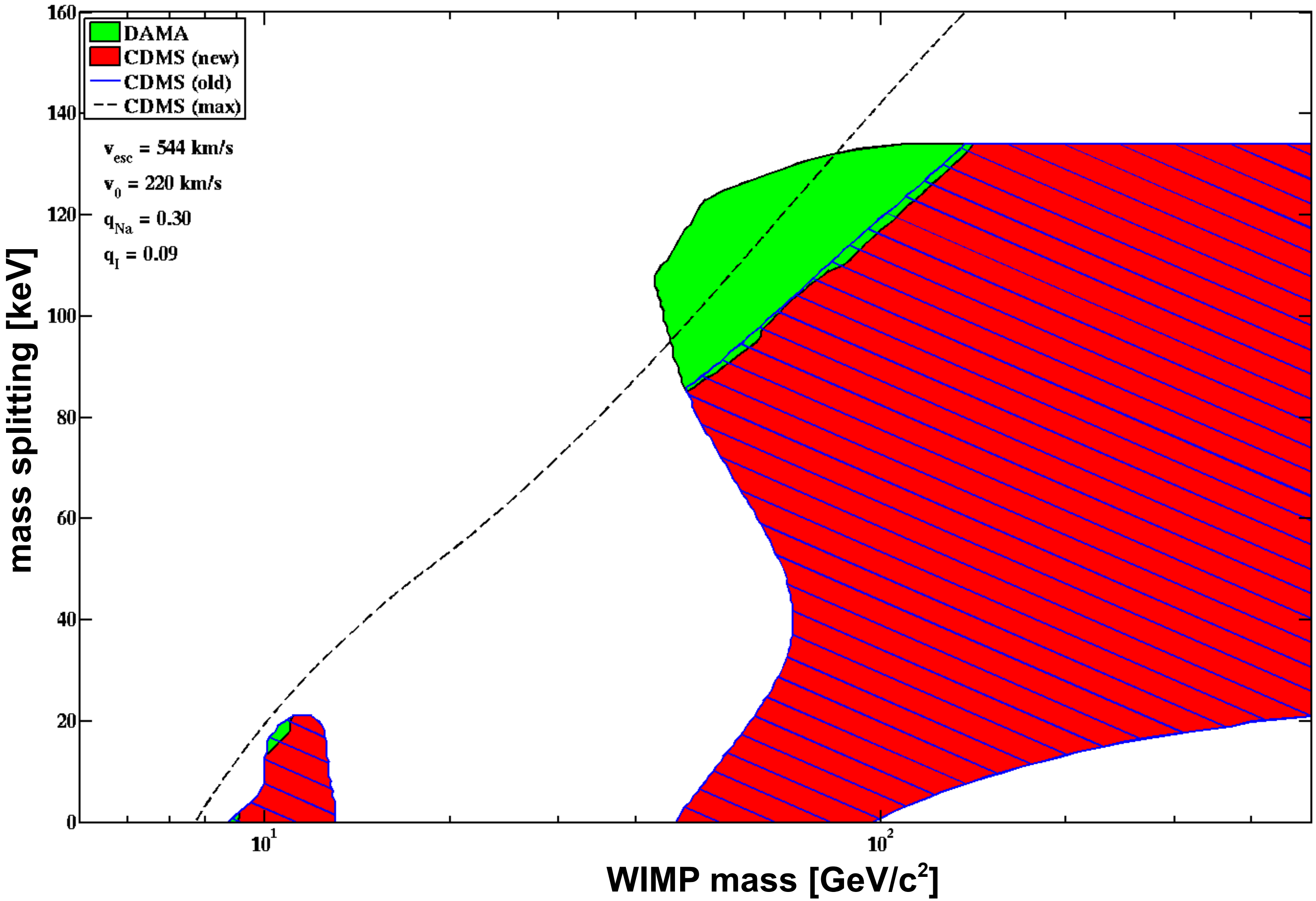


Refined IDM analysis

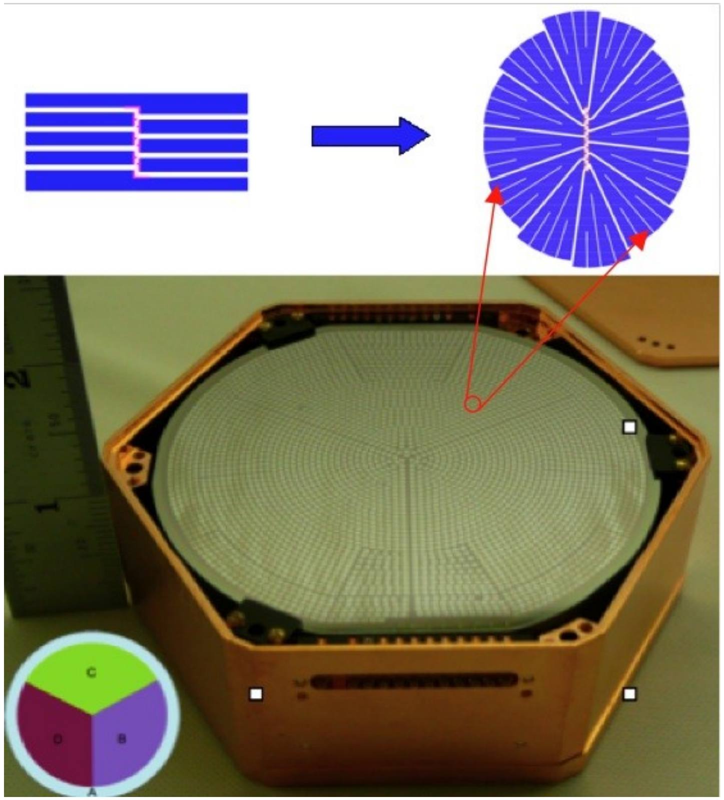
- first CDMS analysis up to 150 keV
- refined surface event rejection cut in 25 - 150 keV energy range
- expected surface event leakage in that energy range: $\mu = 0.83^{+0.45}_{-0.27}\,(\text{stat.})^{+0.30}_{-0.21}\,(\text{syst.})$

3 candidate events:

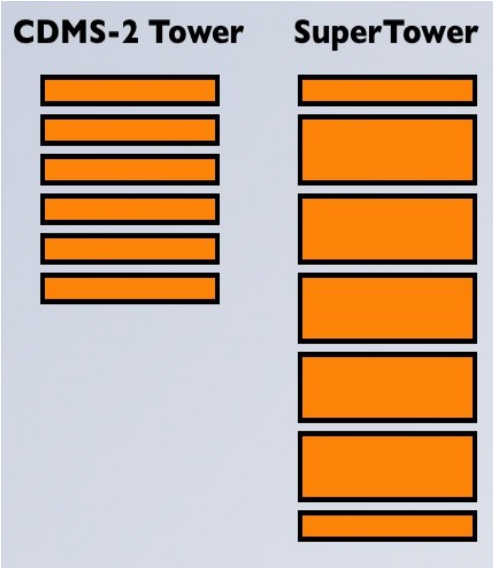
- 37.3 keV
  T4Z6
  (endcap detector)
- 73.3 keV
  T4Z2
  (extremely close to timing cut boundary)
- 129.5 keV
  (far above timing cut boundary)



SuperCDMS



- 2.5 times more massive Ge detectors (1-inch thick)
- reduced surface/volume ratio to decrease background
- endcap Ge veto detectors in each tower
- improved Al fin layout for better phonon collection
- modified phonon sensor layout with outter phonon guard ring similar to outter charge electrode
- first SuperTower data is currently analyzed to evaluate surface event discrimination and detector contamination



Summary

- two candidate events observed

- expected total background (surface events & neutron background): 0.9 ± 0.2

- probability to have two or more background events: 23.3%

- cannot be interpreted as a significant evidence for WIMPs, but none of the two events can be rejected as a WIMP scatter

- world leading upper cross section limit assuming spin-independent scattering for WIMP masses above ~70 GeV

- data taken with first new SuperTower under analysis